0.1 µm METAMORPHIC $In_{0.4}Al_{0.6}As/In_{0.4}Ga_{0.6}As$ HEMTs ON GaAs SUBSTRATE

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ABSTRACT

We report on the fabrication and characterization of 0.1µm T-gate metamorphic InAlAs/InGaAs HEMTs on GaAs substrate with InAs mole fraction of 0.4. These devices present a good Schottky diode behavior, a drain current of 610mA/mm with an extrinsic transconductance of 680mS/mm. An intrinsic transconductance gm_0 of 1150mS/mm and a current gain cutoff frequency f_T of 195GHz are obtained. These good characteristics are similar to those obtained with lattice-matched HEMTs on InP substrate. Metamorphic HEMT is an attractive candidate for large scale and low cost MMIC production in the millimeter wave range.

INTRODUCTION

High electron mobility transistors (HEMTs) on InP substrate have demonstrated superior microwave and low-noise performance over pseudomorphic HEMTs on GaAs substrate. The best results ever reported for HEMTs operating in W-band have been obtained with devices fabricated using InAlAs/InGaAs/InP based material system [1]. This comes from the superior carrier transport properties of the InGaAs channel with a high InAs mole fraction. Unfortunately InP based HEMTs present some drawbacks. InP substrates are mechanically fragile, small and expensive compared with GaAs ones. GaAs substrates are more suitable for large scale MMICs production. An alternative way to avoid InP substrate is to use mismatched strain-relaxed metamorphic (MM) buffers [2-3]. This buffer serves to accommodate the lattice mismatch between the GaAs substrate and the active layers. Using a metamorphic buffer, unstrained InAlAs/InGaAs heterostructure with almost any InAs mole fraction can be grown on GaAs. For instance, a current cutoff frequency f_T of 160GHz was obtained with a 0.13µm gate length HEMT using an $In_{0.52}Ga_{0.48}As$ channel on GaAs substrate [4]. Numerical modeling of InAlAs/InGaAs/GaAs MM-HEMTs [5] predicted an optimum InAs mole fraction of about 0.4 to provide high microwave and low-noise performance in the millimeter wave range.

In this paper, we report DC and microwave performances of $In_{0.4}Al_{0.6}As/In_{0.4}Ga_{0.6}As$ HEMTs on GaAs substrate. The 0.1µm gate length HEMT exhibits an extrinsic current cutoff frequency of 195GHz. This is the best value ever reported on a metamorphic HEMT on GaAs, with an Indium content of 0.4. This value is similar with recent published result [6], which reported a cutoff frequency f_T = 210GHz obtained with 0.1µm gate length MM-HEMT with an Indium content of 0.53.

DISCUSSION

Happy and al [5] reported numerical modeling of InAlAs/InGaAs heterostructure on GaAs. According to this study, an InAs mole fraction close to 0.4 is an optimum value to give high gain and low noise performance. Low-field electron mobility and sheet carrier density in the two-dimensional electron gas were calculated for different InAs mole fraction x. These values are reported in figure 1. As the InAs mole fraction x decreases, the sheet carrier density is improved due to the higher conduction band discontinuity. On the same way, a lower InAs mole fraction x involves a higher bandgap in the InGaAs channel, which contributes to reduce the low field mobility of the electron gas. So, the variation of the InAs content x has two antagonist effects on the characteristics of the heterostructure. This effect will involve high microwave and noise performances for $In_{0.4}Al_{0.6}As/In_{0.4}Ga_{0.6}As$ HEMTs on GaAs substrate and it was found that the optimum InAs mole fraction is 0.4.

Moreover a decrease of InAs mole fraction leads to a high bandgap in InAlAs layer. So, the Schottky characteristics on $In_{0.4}Al_{0.6}As$ will be improved compared to those obtained on lattice matched (LM) structure on InP, which present Indium content close to 0.53. This behavior will give high turn-on and gate breakdown voltages, and will allow larger voltage operation for 0.4 MM-HEMT than for LM-HEMT.

MATERIAL GROWTH

Metamorphic InAlAs/InGaAs HEMTs layers (MM-HEMTs) were grown on (100)-oriented GaAs substrate using a Riber-32P Molecular Beam Epitaxy Machine. To accommodate the lattice mismatched between the active layer and the GaAs substrate, a metamorphic buffer layer has to be grown. We use an inverse step-graded buffer of InAlAs [3]. Figure 2 shows the schematic cross section of the epitaxial structure. The buffer consists in the growth of 1µm of InAlAs with an Indium content varying from 0.01 to 0.5. This first layer was grown at low temperature substrate (T_s = 400°C) to avoid island formation. Then a 0.3µm thick layer of InAlAs was grown with an Indium content of 0.4. During the realization of this layer, the growth temperature was increased to 500°C. Finally the active layer of MM-HEMTs is realized. The Hall mobility and sheet carrier density are respectively $4.16.10^{12}cm^{-2}$ and $8250cm^2/Vs$ at room temperature. The mobility is enhanced to $26000cm^2/Vs$ with a sheet carrier density of $3.44.10^{12}cm^{-2}$ at 77K.

DEVICE FABRICATION

The $0.1x100\mu m^2$ T-shaped gate devices were fabricated as follows. First, the mesa was defined by wet chemical etching using H_3PO_4:H_2O_2:H_2O (5:1:40) solution. To form ohmic contacts, Ge/Au/Ni/Au metalization was evaporated and followed by rapid thermal annealing. TLM measurements give typical ohmic contact resistance of about 0.18Ω.mm. Then a 800Å silicon nitride film is deposited. This dielectric layer will serve to support the top of the T-gate. This allows to obtain high fabrication yield due to the reduction of the footprint gate breaking during lift-off process. The 0.1µm footprint gate was defined by electron beam lithography and the silicon nitride opening with a non-isotropic CHF_3/CF_4 reactive ion etching process. The top of the T-gate was defined using a two-layer PMMA/(PMMA-MAA) resist. Selective gate recess etching was performed using Succinic Acid, ammonia and hydrogen peroxide solution (SA:NH_4OH:H_2O_2). The etching selectivity ratio of InGaAs over InAlAs was higher than 300. The gate metalization consisted of Ti/Pt/Au. Finally, thick Ti/Au layers were evaporated to form bonding pads.

DC AND MICROWAVE CHARACTERISTICS

DC-characteristics of $100x0.1\mu m^2$ MM-HEMTs was performed on wafer. Values of drain to source current I_{ds} and transconductance gm versus gate to source voltage V_{gs} are reported in figure 3. The device exhibits a maximum drain to source current I_{ds} of 610mA/mm for a gate to source voltage V_{gs} of 0.6V. The maximum extrinsic transconductance is 680mS/mm. Schottky characteristic measurement gives a forward turn-on voltage of 0.7V and a gate breakdown voltage of -6V. Improvement of Schottky barrier quality, with respect to typical results on lattice-matched HEMTs, is due to the higher bandgap of the $In_{0.4}Al_{0.6}As$ layer.

On-wafer S-parameters measurements of a 100x0.1µm² MM-HEMT were realized. From these measurements, extraction of small signal equivalent circuit was performed in the 0.5-50GHz-frequency range. Intrinsic transconductance gm_0 and output conductance gd are plotted in figure 4. The device exhibits a maximum transconductance gm_0 of 1150mS/mm at I_{ds} = 260mA/mm. At same current I_{ds}, an output conductance of 161mS/mm is obtained. Extrinsic current gain $|h_{21}|^2$ is represented in figure 5. Extrapolated cutoff frequency f_T is 195GHz. This result can be compared with typical f_T of about 200GHz obtained with 0.1µm LM-HEMTs on InP substrate using the same technology.

CONCLUSION

0.1µm metamorphic InAlAs/InGaAs HEMTs with InAs mole fraction of 0.4 on GaAs substrate have been successfully realized. A drain-to-source current I_{ds} of 610mA/mm was obtained. Metamorphic devices present good Schottky diode breakdown voltage. Microwave characterizations give current gain cutoff frequency f_T of 195GHz and an intrinsic transconductance gm_0 of 1150mS/mm. In spite of an Indium content of 0.4, such devices exhibit results comparable with some obtained with lattice-matched HEMTs on InP substrate with the same gate length. Metamorphic $In_{0.4}Al_{0.6}As/In_{0.4}Ga_{0.6}As$ HEMTs demonstrate high performance and its potentiality for large scale and low cost MMIC production in the millimeter wave range.

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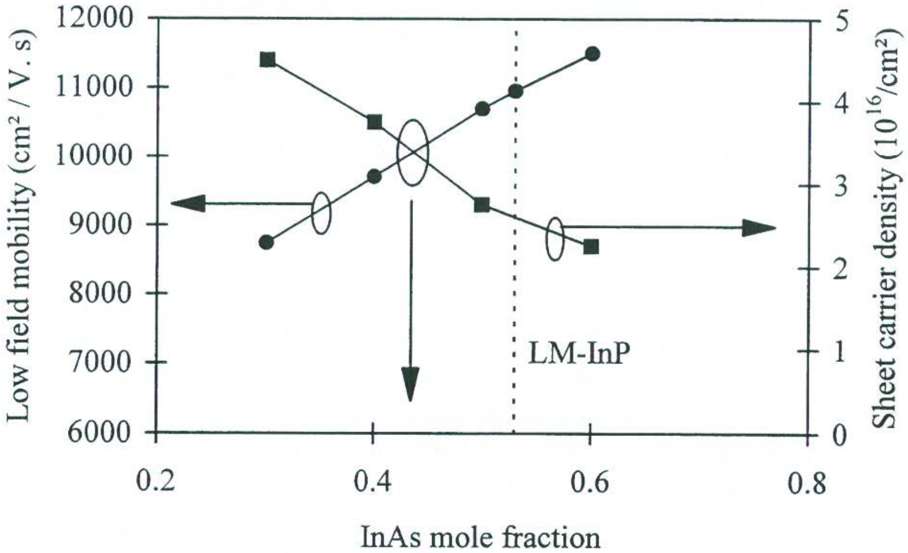

Figure 1 Calculated low field mobility and sheet carrier density in the InGaAs channel versus InAs mole fraction.

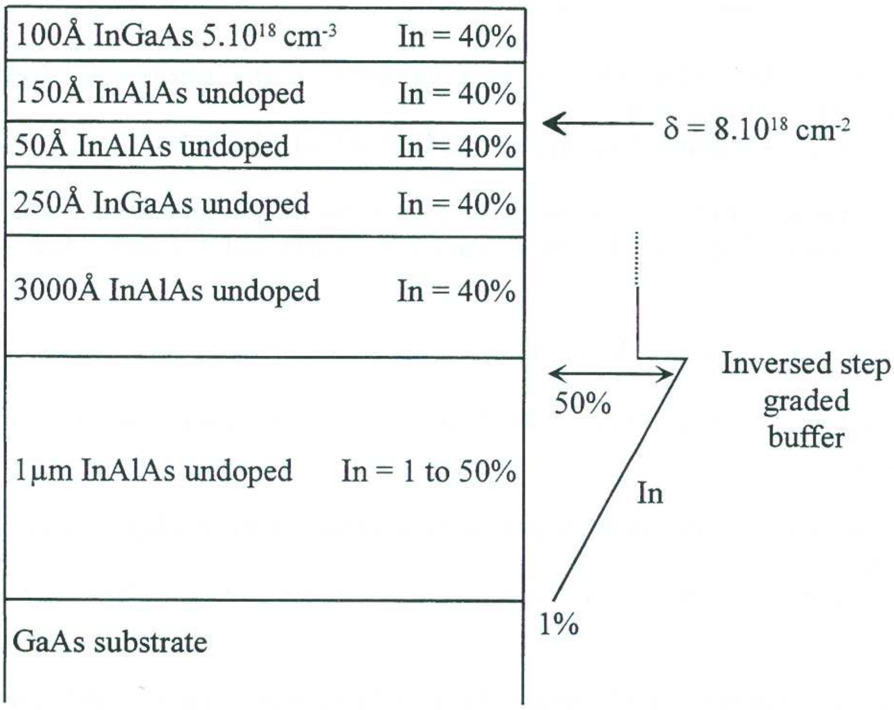

Figure 2 Schematic cross section of MM-HEMT structures on GaAs substrate

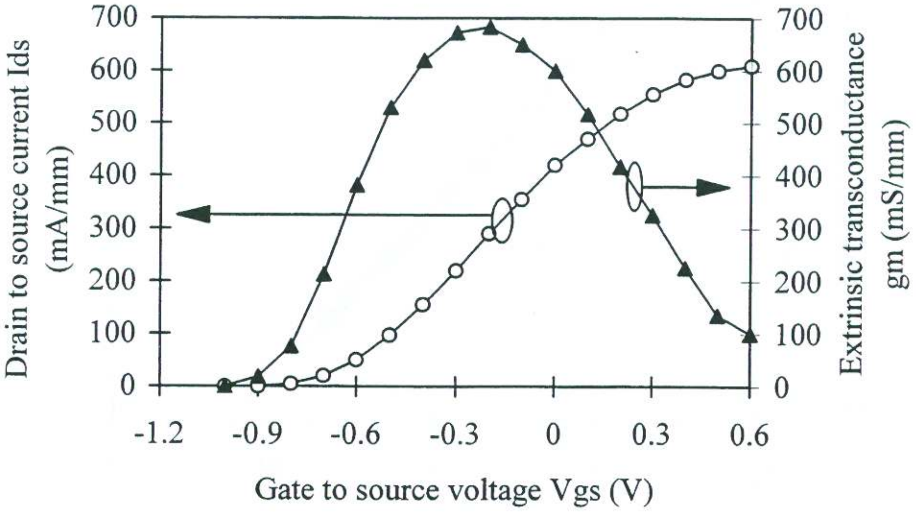

Figure 3 Drain to source current I_{ds} and extrinsic transconductance gm of 0.1µm MM-HEMT versus gate to source voltage V_{gs}

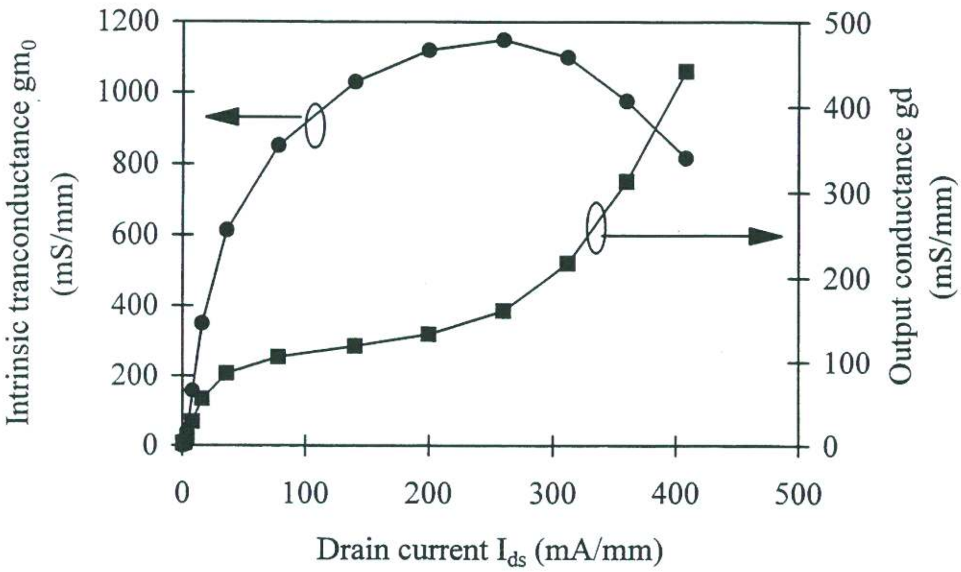

Figure 4 Intrinsic transconductance gm_0 and output conductance gd versus drain current I_{ds} for a 0.1µm MM-HEMT.

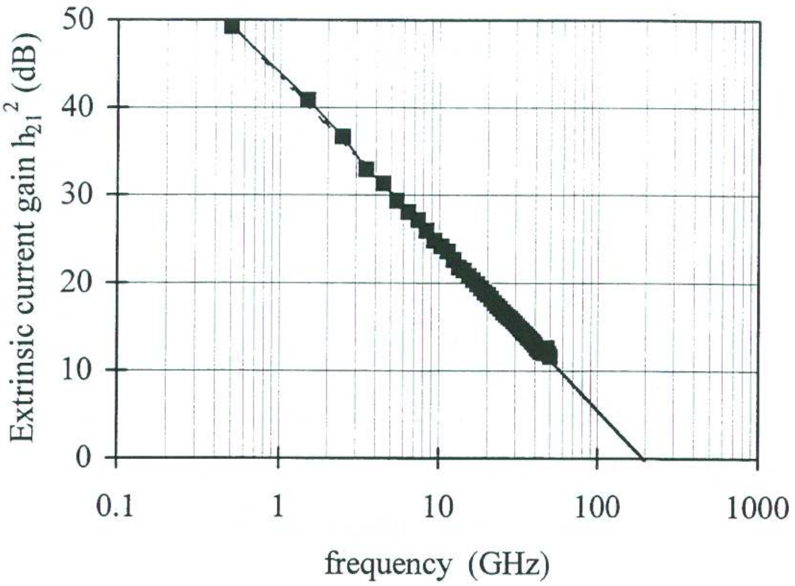

Figure 5 Extrinsic current gain h_{21}^2 versus frequency for a 0.1μm MM-HEMT